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Robotized stator cable winding

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A R T I C L E I N F O

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A B S T R A C T

Automated stator winding assembly has been available for small and medium sized conventional electric machines for a long time. Cable winding is an alternative technology developed for medium and large sized machines in particular. In this paper we present, evaluate and validate the first fully automated stator cable winding assembly equipment in detail. A full-scale prototype stator cable winding robot cell has been constructed, based on extensive previous work and experience, and used in the experiments. While the prototype robot cell is adapted for the third design generation of the Uppsala University Wave Energy Converter generator stator, the winding method can be adapted for other stator designs. The presented robot cell is highly flexible and well prepared for future integration in a smart production line. Potential cost savings are indicated compared to manual winding, which is a backbreaking task. However, further work is needed to improve the reliability of the robot cell, especially when it comes to preventing the kinking of the winding cable during the assembly.

1. Introduction

In 2009, a project on robotized stator cable winding was initiated at UU.[1] The aim of the project was to investigate the possibility of automating the winding assembly of cable wound electric machines. During this project, a robotized cable winding method has been developed [1–5]. The method has been adapted for the cable wound UU WEC[2] generator stator [6–7], see Fig. 1, which was used as an application example. The stator of the UU WEC linear generator stator is divided into sections which are wound separately. Different stator designs have been used, with a different number of sections as well as both straight and angled sections. Winding specific terms related to the stator section are explained in Fig. 2. To smoothen the fluctuating power output from single point absorbing UU WECs and to make the concept highly scalable, multiple units should be deployed together and coupled to marine substations before grid-connection [8].

In the first UU work on robotized cable winding, we introduced a robotized cable winding system and evaluated and compared it to manual cable winding as well as to other winding methods [1]. The suggested robot winding procedure was to have industrial robots—equipped with cable feeder tools and assisted by automated cable preparation and temporary cable storage equipment—winding a stator section in pairs, by alternately pushing and pulling the cable through slot holes in the stator section and between each other. It was clear that robotized cable winding could significantly reduce the assembly cost compared to manual cable winding. In the following work, we demonstrated robotized stator cable winding, including six-degrees-of-freedom stator positional calibration of the stator section WOCS,[3] with manual supervision and manual cable preparation, in full-scale with promising results. Here, the second generation UU WEC generator was used as an example [2–3]. Finally, an updated cable feeder tool adapted for more durable and flexible robotized cable winding and fully automated robotized cable preparation equipment was demonstrated and evaluated with very promising results in our most recent work [4–5]. At the same time, the UU WEC concept reached the third design generation and is currently commercialized by the spin-off company Seabased Industry AB. Here, large-scale automated production will likely be necessary to compete on the global energy market. The automated stator cable winding in particular will need to be prioritized as it is a backbreaking, monotone, labour intense and time consuming manual task. High quality and durable stator winding is also critical since, after being deployed off-shore where maintenance will be complicated and expensive, the WEC will occasionally be subjected to very rough wave climates. This exemplifies the need for a stator cable winding automation prepared for industrialization.

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[1] Uppsala University.
[2] Wave Energy Converter.
[3] Work Object Coordinate System.

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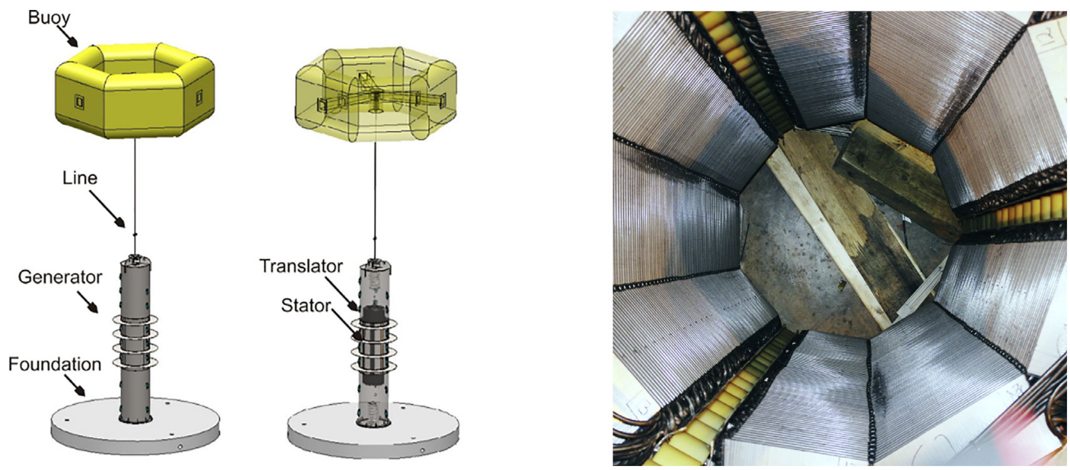


Fig. 1. (a) The UU WEC unit, with a linear direct-drive, permanent magnetized cable wound generator placed on the seabed and coupled via a line to a point-absorbing buoy. (b) A nine-sided stator, assembled from three double-angled cable wound stator sections, inside a UU WEC generator hull.

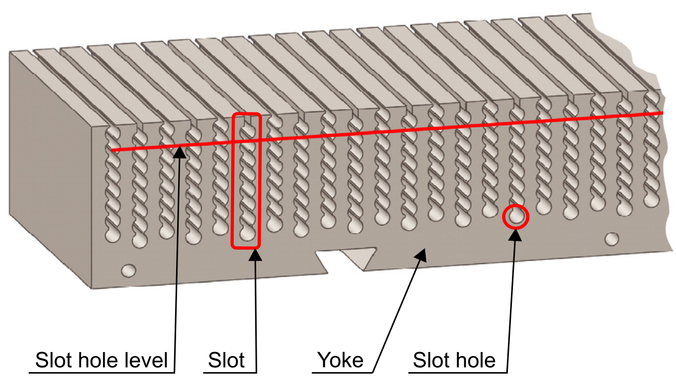


Fig. 2. Stator section terms explained.

Cable winding is an alternative stator winding technology developed particularly for medium and large sized generators, motors and transformers [9–11]. The potential benefits with cable wound machines include few winding assembly steps, high efficiency and durable performance. Beyond being used in the UU WEC generator, cable winding has also been used for example in offshore motor installations [12], motors for electric vehicle propulsion systems [13] and in generators for hydropower [14], thermal energy [15], wind energy [16] and hydrokinetic [17] power plants. With the liberalization of electricity markets and increased environmental concerns leading to an increased number of distributed electricity generation systems [18], it is likely that the demand for medium and large sized generators will increase. Hence, there are many possible applications where automated cable winding could be used.

The development of advanced, adaptable automated assembly systems with high flexibility has been prioritized in response to a global and fast changing market [19–20]. While modern automation technology offer huge potentials, rapid evolution and high flexibility, the system complexity typically rise accordingly. To achieve successful industrial implementation, reliability is crucial and connectivity is increasingly emphasized [21]. The stator winding of especially small and medium sized conventional electric machines produced on a large scale is an example of where automated assembly solutions have been present for a long time [22–24]. Recent developments focus mainly on facilitating and increasing the flexibility and efficiency of the assembly [25–30]. Stator cable winding, on the other hand, has not been automated elsewhere. However, other applications with similar automation concepts are filament winding [31], the winding of edge localized mode control coils for tokamaks [32], tape winding [33], fiber optic winding [34] and wire harness assembling [35]. Another interesting application is cable laying performed with cable feeder tools [36].

A major challenge of robotized cable winding is the handling of the flexible cable. The previously presented robot cell layout and cable feeder tool design provided full cable localization and handling capabilities. Undesired twisting of the cable during winding, on the other hand, is more difficult to prevent. Torsional forces on the cable could cause formation of self-contacting cable loops. These could in turn damage the cable or interfere with upcoming windings if the cable does not pop out easily and completely as the cable end winding between two slot holes is pulled to its final shape. Such cable kinking behaviour is more likely to arise if torsional-stiff and easy-to-bend cables with helical multi-thread conductors are used [37–40]. The investigated cable winding method uses short end windings with small radii. As observed in [3], because easy-to-bend winding cables are preferred and the end winding cable is not axially tensed, cable twisting brings a significant risk for winding failures and must therefore be prevented in the first place. Sensor-based methods for localization and manipulation [35,41–42] as well as analytical methods for shape prediction and automatic routing [43–44] of similar objects have previously been demonstrated in the literature.

With the promising previous work and the potential multiple applications in mind, we decided to develop the robot cable winding method further with regards to durability, quality, flexibility, adaptability and productivity. To prepare the robot cell for industrial production line integration, we also decided to further develop the extensive robot cell control system with regards to simplicity, effectivity,

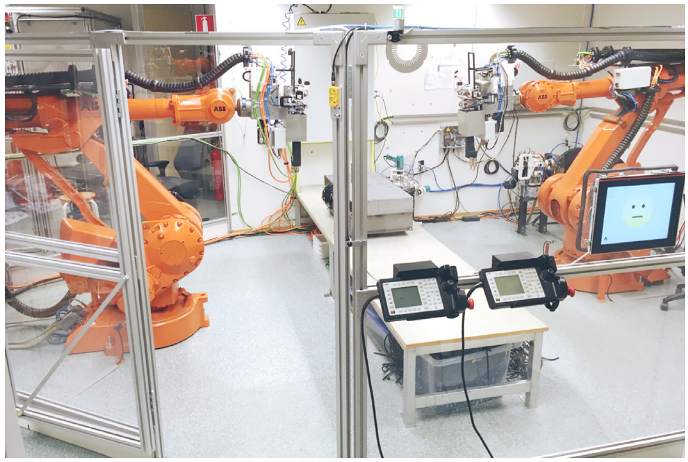


Fig. 3. The constructed robot cell used during the robotized cable winding experiments.

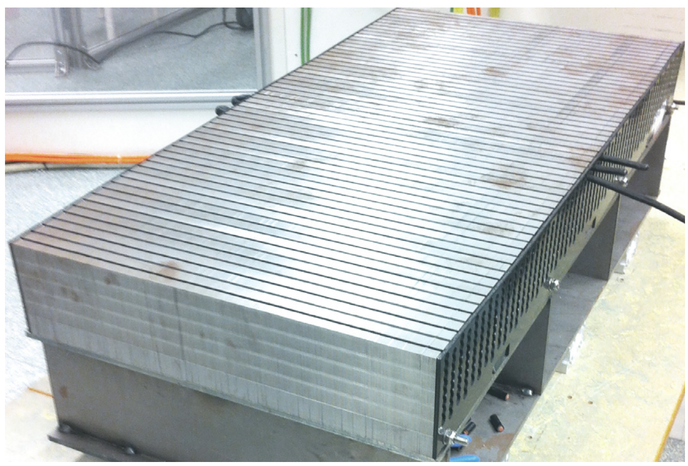


Fig. 4. The UU WEC stator section part used during the robotized winding experiments.

user friendliness, evaluability, traceability and adaptability. The aim of this paper is to present the new stator cable winding robot cell, including the equipment design, the control system design and the evaluation through full-scale experiments. The UU WEC generator stator is again used as a reference and the updated robot cell is adapted for the third generation UU WEC design. In the following, the experimental setup and method used in this work are presented in Section 2, the equipment layout, the control system design and the operator user interface are presented in Section 3, the experimental results are presented in Section 4, the results are discussed in Section 5 and conclusions are given in Section 6.

2. Experimental setup and method

We developed and constructed an updated stator cable winding robot cell using the available equipment, see Figs. 3 and 4. Experience from previous manual and robotized winding was taken into account and the previous robot winding method [3] was used as a starting point. However, the updated winding equipment provided more extensive control abilities, the winding process was significantly updated and the robot cell control system was redesigned completely. We also made adjustments for the third generation UU WEC design, including using a straight stator section about 500 mm wide and wound with $25\,\mathrm{mm}^2$ cable instead of the previous angled stator section with $16\,\mathrm{mm}^2$ cable.

The updated experimental setup included the three previously constructed updated cable feeder tools—described in detail in [5]—, the previously constructed automated cable preparation equipment—-described in detail in [4]—, an ABB AC500 PLC[4]—the same PLC used to control and supervise the cable feeder tools and the cable preparation equipment, hereafter referred to as *the PLC*—, an ABB CP675 HMI[5] 15″ colour touch panel, a desktop PC—used for programming and file transfer—, two ABB IRB4400/60 kg M2000 S4C + industrial robots—hereafter referred to as *R1* and *R2*—, a 1 m long UU WEC stator section part and a PVC-insulated multi-thread winding cable delivered on 250 m cable drums. We used industrial safety devices, including fences and two ABB Pluto B20 safety PLCs—hereafter referred to as *the safety PLCs*—, to fulfil the required safety standards. All equipment was completely assembled, programmed and evaluated in-house. The programming was an extensive, iterative and integrated process, where solutions to different sub-problems needed to be solved simultaneously and multiple adjustments and calibrations were required before a satisfying solution was found. The user interface was evolved simultaneously. In the following, for clarity, the final robot cell layout, control system design and user interface are explained piece by piece and the experimental evaluation is presented for the final robot cell.

The full-scale winding experiments performed to evaluate and

[4] Programmable Logic Controller.

[5] Human-Machine Interface.

Table 1
The most essential requirements for the updated stator cable winding robot cell, including priority where A is more critical than B.

Requirement	Priority
Adapted for the third generation UU WEC stator	A
Durable and failsafe performance	A
Minimal operator time required	A
High winding process flexibility	A
Prepared for production line integration	A
Simple but powerful operator interface	A
Low process cycle times	B
Relevant operator process feedback	B
Integrated production data logging	B
Simple commissioning	B
Scalable design	B

validate the final robot cell were completely automated and included full evaluation of the user interface. Critical process parameters as well as relevant process events and process statistics were automatically logged during the complete winding process. Video recording was used to facilitate the evaluation of the process. We performed numerous and extensive experiments in order to identify even rarely occurring failures and thus achieve a durable performance.

To estimate the complete UU WEC stator winding process cycle time, we defined detailed sub-process cycle times from process recordings and extrapolated these analytically. The same analytical method was used to estimate the corresponding process cycle times for other winding scenarios, including different stator designs and further process improvements. The 3D-CAD software SolidWorks and the industrial robot simulation software ABB RobotStudio were used to evaluate different robot cell layouts. In the analytical evaluation, we used manual winding as a reference and included different stator section designs as well as further developed robot winding scenarios. To facilitate comparison with the previous economical evaluation of the robot winding process [1], we used the same net present value calculation method and similar calculation parameters when performing an economical evaluation for the updated robot cell against manual winding.

3. Robot cell design

The most important updates of the new robot cell, besides the new equipment, was the use of a powerful industrial PLC as the main process controller and using a separate and powerful industrial HMI. Table 1 summarizes the requirements that the updated robot cell should fulfil, while the layout of the updated robot cell and its control system are explained together with robot cell equipment definitions in Fig. 5. All equipment was connected to the PLC. Both the PLC cabinet and the servo motor drive cabinet were prepared for future integration of additional equipment.

To make the integrated equipment and winding process control system as neat, effective, reliable and user friendly as possible, overall process control was given to the PLC. Meanwhile, all the safety programming was distributed to the safety PLCs and all the robot programming was distributed to the robot controllers. Hence, the winding process control system was distributed between the PLC and the robot controllers. To achieve a distinct winding process control system hierarchy, the winding process control system in the robot controllers was organized into different procedures. These procedures were in turn called from the PLC as a winding process was initiated by the operator from the GUI[6] at the HMI touch panel. To add flexibility to the control system, we used a parameterized work object and parameterized equipment definitions. These parameters were used in the control system when automatically calculating and updating the winding process parameters, such as the position of the next slot hole to wind and the current required cable feed length. With an extensive and rather complex control system, a lot of work was put into developing a powerful yet simple operator user interface.

In the rest of this section, the PLC winding control system is presented in Section 3.1, the robot controller winding control system is presented in Section 3.2 and the operator user interface is presented in Section 3.3.

3.1. PLC winding control system

The PLC winding control system was divided into different sub-programs, used for different winding procedures, process control, communication, supervision, error handling and data logging. Only the currently required sub-programs were processed.

In the rest of this section, the PLC main winding procedure sub-program is explained in Section 3.1.1, an overview of other essential PLC winding control system sub-programs is given in Section 3.1.2 and an overview of error handling and process logging in the PLC winding control system is given in Section 3.1.3.

3.1.1. The winding procedure

A complete cable winding procedure, see Fig. 6, started with the operator defining the winding parameters. These parameters included the choice of the winding pattern, the choice over which slot holes the winding should be performed and in which slot hole the winding should begin. The PLC then calculated the number of cables, the cable lengths and the estimated total process cycle time, before the operator confirmed the initiation of the winding procedure. First, the robots positioned their tools to wait in front of the stator section before the positional calibration of the stator section WOCS was initiated. When the positional calibration was finished, the amount of cable left on the cable drum was compared to the length of cable required for the next cable to be wound. If there was not enough cable left, the robot cell was paused and the operator was asked to replace the cable drum. Next, a cable was fetched by R1 at the cable drum equipment and prepared in the cable end preparation equipment. The prepared cable was then wound into the stator section by the two robots, according to the winding parameters adjusted for the current cable. Before another cable was wound, the winding parameters were updated for the next cable to be wound. If the operator had requested a pause, the robot cell was paused until the operator restarted it. Next, the winding procedure was rewound to the point where the amount of cable left on the cable drum was evaluated. Finally, when all the cables had been wound, the robots were moved back to their home positions.

3.1.2. Other winding procedures

We implemented specific start-up, shutdown and reset procedures for all robot cell equipment in the PLC control system. It was also possible to initiate the PLC control system without starting up all the equipment, in order to be able to perform e.g. equipment calibration processes. Specific service and calibration procedures were also developed. These procedures included functions to reset or edit tool statistics, to update the default parameters, to move the robots to predefined positions and to perform the automatic cable feeder tool calibration procedures described in [5].

We developed separate functions for stopping, freezing and pausing the robot cell. The stop function was used to immediately stop the process and all the equipment without consideration for machine safety or easy restart. The freeze function was used to halt the winding procedure at the next suitable occasion, e.g. for inspection purposes, with consideration for machine safety and easy restart. The pause function was similar to the freeze function, but waited until the present cable was completely wound. A safe stop was triggered by pushing an emergency stop button or opening the cell enclosure door and was performed by the safety PLCs.

[6] Graphical User Interface.

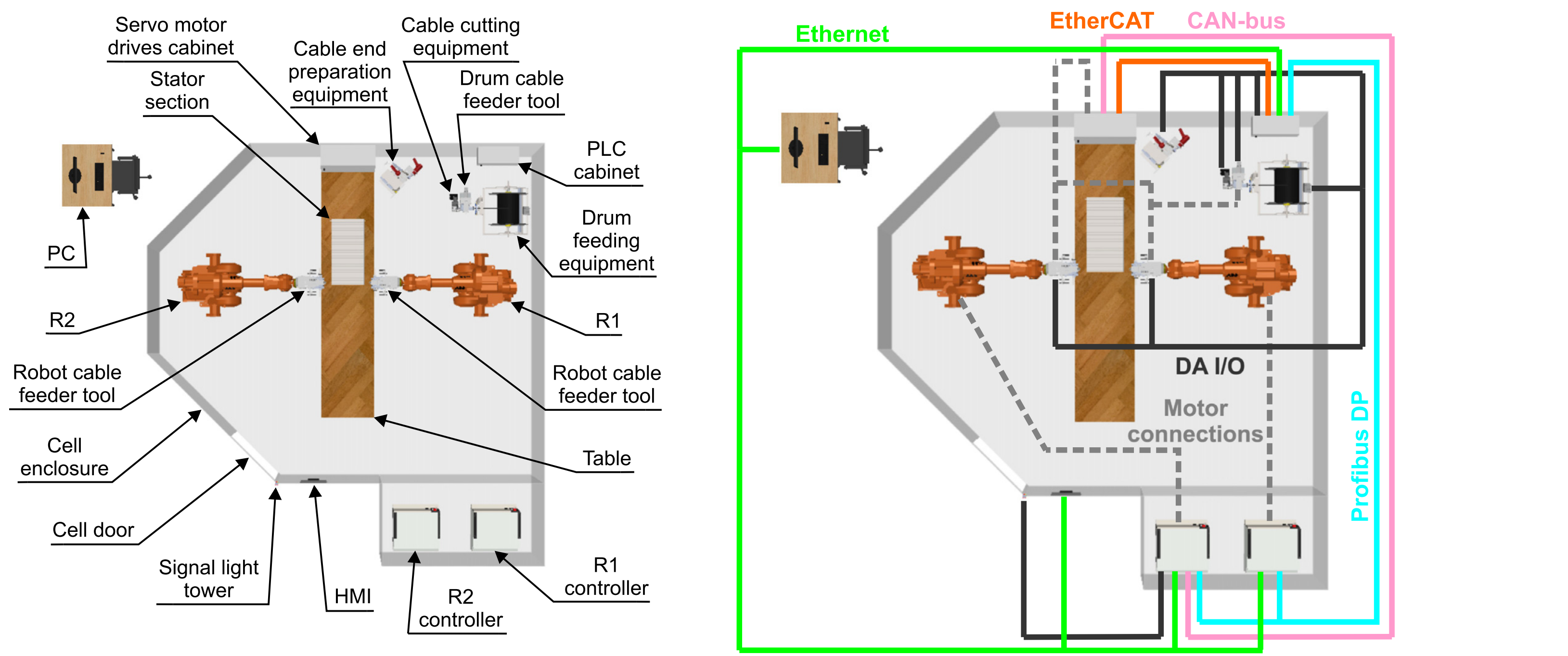


Fig. 5. (a) The layout of the updated robot cell. (b) The physical control system connections for the updated robot cell. The two safety PLCs—installed with the R2 controller and in the servo motor drives cabinet—communicated using CAN-bus and connected to the PLC using Profibus DP, through a gateway.

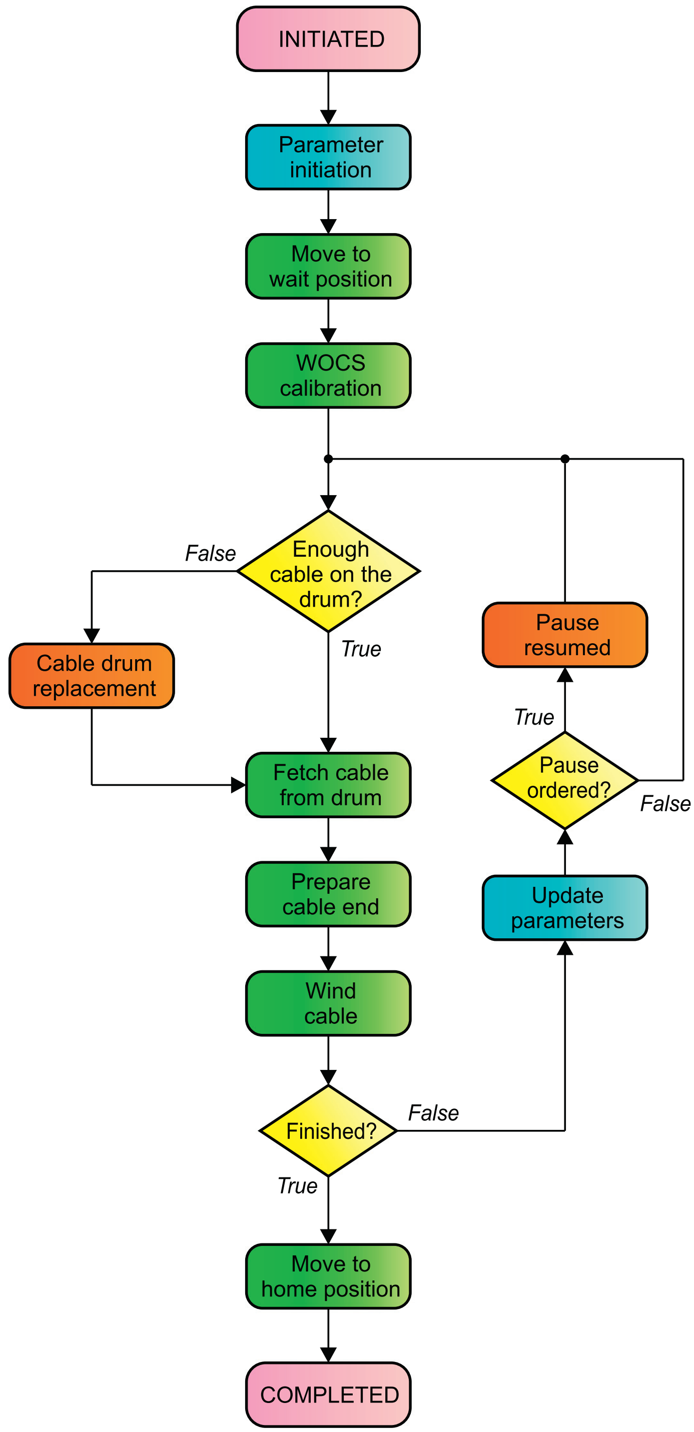


Fig. 6. An illustration of the PLC cable winding procedure, where pink boxes represent the procedure start and end, yellow boxes represent the evaluation made in the PLC, blue boxes represent the PLC actions, green boxes represent the robot actions and orange boxes represent the cell operator actions.

The robot positioning, the stator section positional calibration, the cable end preparation and the single cable winding sub-procedures could be started separately. Variations of these procedures were also possible, such as using the default or the previous measured stator section WOCS instead of performing the positional calibration procedure, fetching a cable with an already prepared end from the drum cable feeder tool and winding a cable without cutting it off.

3.1.3. *Error handling and logging*

We integrated a simple error handler, for errors raised in any part of the control system or in any of the connected equipment, in the control system. Non-fatal error events were as far as possible solved with— in order of priority—integrated automated error handling, operator dialogs or operator warning messages. For example, if the cog wheels in a cable feeder tool were not fitted angularly, a cog wheels fitting function [5] was automatically called before a cable was gripped, a failed cable end insulation pull-out length inspection [4] initiated an operator dialog to determine if the cable end should be used anyway or discarded and a warning message was raised if equipment service was needed. Other errors with unclear causes, which should normally never occur, were treated as fatal and triggered a momentary stop of the present procedure and all the equipment.

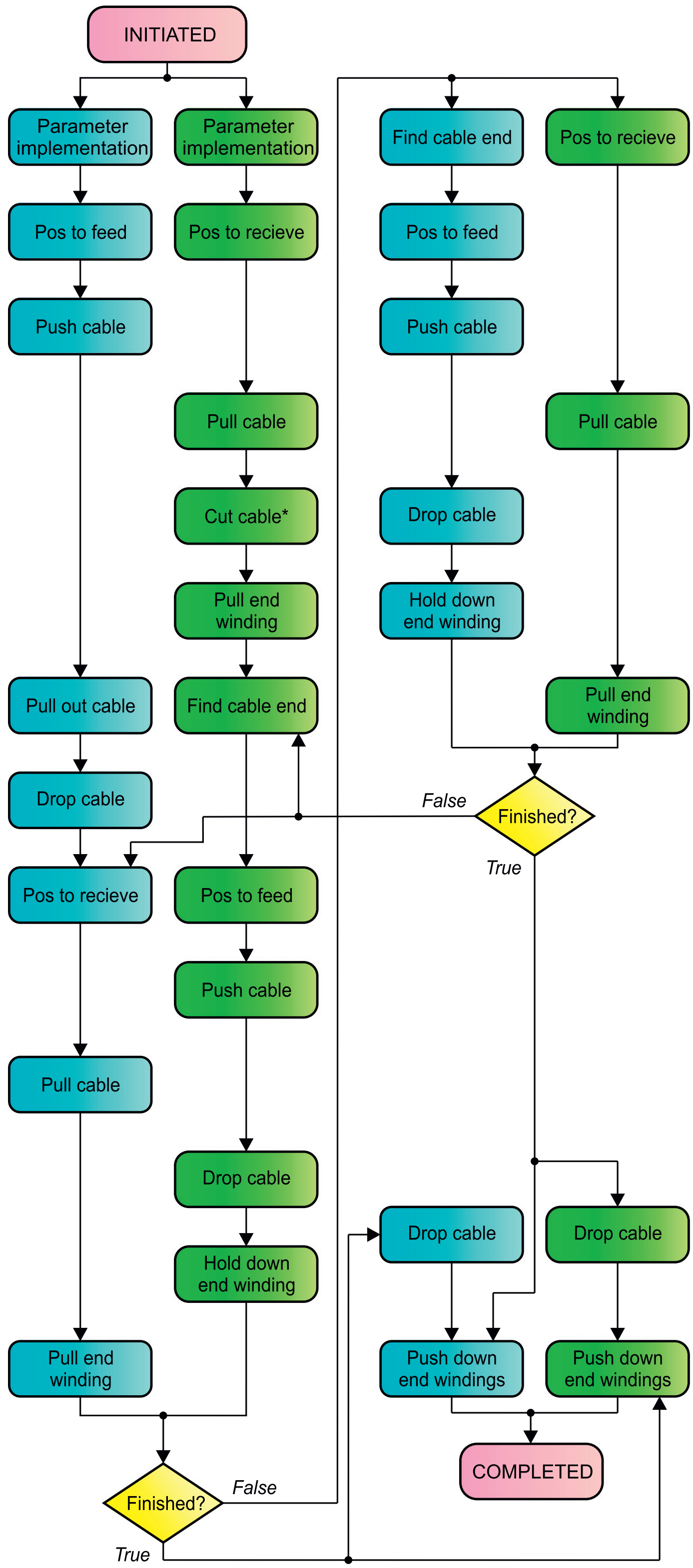


Fig. 7. An illustration of the robot controller sub-procedure for winding one cable, where pink boxes represent the sub-procedure start and end, yellow boxes represent the evaluation made in the robot controllers, blue boxes represent R1 actions and green boxes represent R2 actions.

To facilitate the evaluation of the robot cell performance, the PLC control system automatically logged all essential events, parameters and statistics, such as an error being raised, the length result from a completed cable end insulation pull-out length inspection and sub-process cycle times for a completed winding procedure, and copied these to an SD-card. To enable a more detailed performance evaluation, an extended process logging option was also available. This included continuous logging of essential equipment and process parameters, such as the current feed forces achieved in each cable feeder tool and the current PLC CPU load.

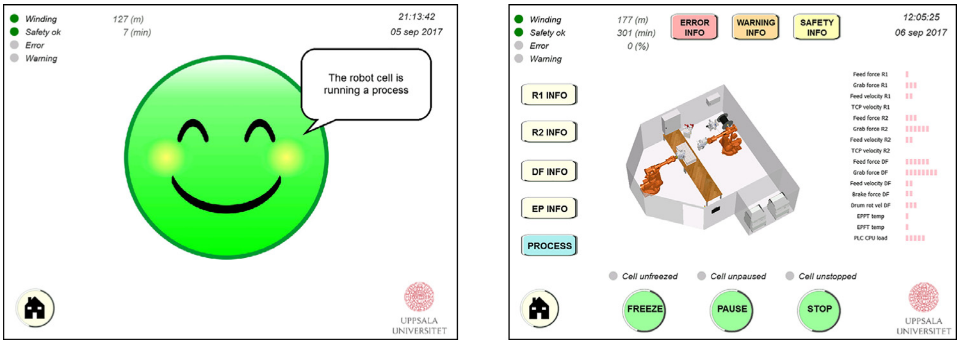


Fig. 8. (a) An example of a simple status page as displayed in a simpler operator level on the GUI. (**b**) An example of a detailed cell status page as displayed in a more advanced operator level on the GUI, extensive detailed parameters including trend plots, average values and extreme values are available for each connected equipment from the sub-menus.

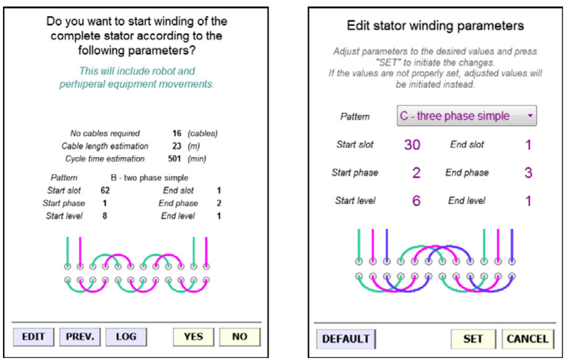


Fig. 9. (a) An example of a winding process initiation window on the GUI. (b) An example of a custom winding parameter choice window as displayed in a more advanced operator level on the GUI.

3.2. Robot controller winding control system

The robot controller winding control system was divided into numerous sub-procedures, used for different winding processes, actions, calculations and communication. In correlation with the PLC control system, we developed specific start-up, shut-down, reset and equipment service procedures and different winding procedures could be activated separately in the robot winding control system. The control system was processed line after line, with trap functions for supervising error, stop, freeze and reset signals from the PLC.

As seen from the PLC side, in Fig. 6, six different sub-procedures were used during winding: moving the robots to their wait positions, performing positional calibration of the stator section, fetching a new cable, preparing the cable end, winding the cable into the stator section and moving the robots to their home positions. Moving the robots to their wait and home positions was very straightforward and the cable preparation sub-procedure is described in detail in [4]. In the rest of this section, the positional calibration sub-procedure is explained in Section 3.2.1 and the sub-procedure for winding a cable is explained in Sections 3.2.2–4.

3.2.1. WOCS calibration

To achieve a simple but efficient and accurate positional calibration for the new stator design, the previous positional calibration procedure [2] was used as a starting point. Since the updated robot cable feeder tools were equipped with sensors enabling high accuracy positioning against the stator section side [5], the previous x-offset stator section side measurements were no longer needed. We used older and not absolute calibrated industrial robots, which was a challenge for measuring and positioning against a longer stator section. To compensate for the limitations in absolute positioning accuracy, we developed robot and task specific absolute positioning compensation matrixes. These matrixes were defined manually for each robot before the robot cell was commissioned by positioning the robots—with the feeding and receiving ends of the cable guiding system respectively—at pre-defined targets over a stator section side and measuring the deviation from perfect accuracy.

3.2.2. The winding procedure

As the sub-procedure for winding a cable into the stator section was started, see Fig. 7, procedure specific winding process parameters were first calculated and implemented according to the winding parameters specified for the cable in the call from the PLC. To begin with, R1 was holding a prepared cable fed from the cable drum and both robots were at their wait positions. Then, the robots were positioned against the first slot hole to be wound, while cable was fed synchronized to the movement of R1 from the drum. R1 then fed the cable through the stator section, while cable was fed synchronized to R1 from the drum, until the cable end was detected by R2. Next, R2 pulled the remaining required cable length through the stator section, while cable was fed simultaneously to R2 from the drum. When the total required cable length had been fed from the cable drum—in any of the presented cable feed operations—the feeding was paused and the cable was cut off from the drum as described in [4]. R1 was then moved back from the stator section side following the cable and positioned in front of the drum cable feeder tool, where it pulled out the cut cable end as described in [4], and then dropped the cable. Simultaneously, R2 was moved back from the stator section side following the cable and then fed the cable backwards through the tool while searching for the cable end as described in [5]. Next, both robots were positioned against the next slot hole to be wound. R2 then fed the cable through the stator section until the cable end was detected by R1. Now, R1 pulled the cable through the stator section until just enough cable remained in the end winding for R2 to follow the cable back from the stator section side and drop the cable. After dropping the cable, R2 was positioned above the end winding to be pulled, with the push handle directed downwards, to hold down the end winding to be pulled. Thus, the risk of cable twisting was reduced significantly when R1 then pulled the cable until a well-defined end winding was formed between the two slot holes. The winding procedure was then repeated with R1 and R2 shifting roles, beginning with R1 searching for the cable end and ending with R2 pulling the end winding. This winding procedure was repeated until the cable was completely wound. Finally, the cable was dropped completely and both robots were positioned above the pulled end windings, with their push handles directed downwards. The robots then pushed down the end windings before moving back to their wait positions.

3.2.3. Winding sub-procedures

Several additional winding-specific sub-procedures were used in the sub-procedure for winding a cable, of which the essential ones are explained here. To begin with, two separate sub-procedures were used for positioning the robot cable feeder tools against a slot hole on the stator section side with the feeding end TCP[7] and the receiving end TCP of the

[7] Tool Center Point.

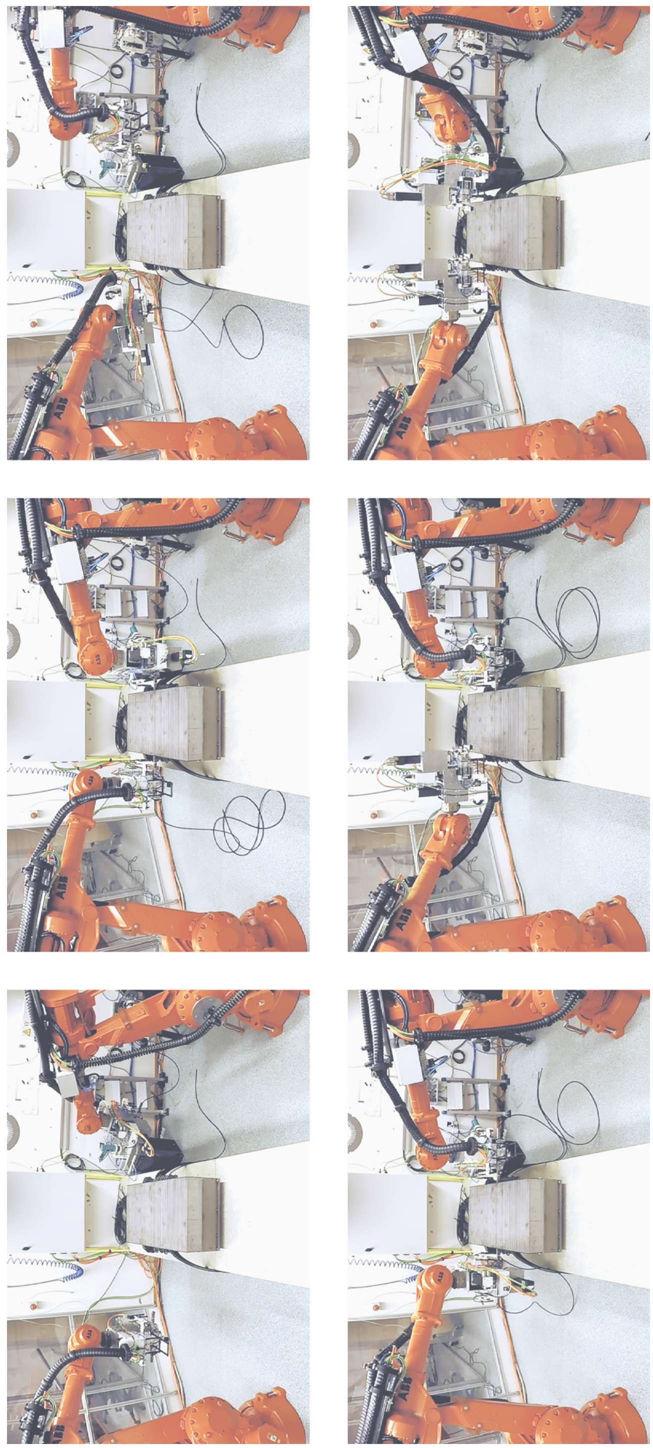
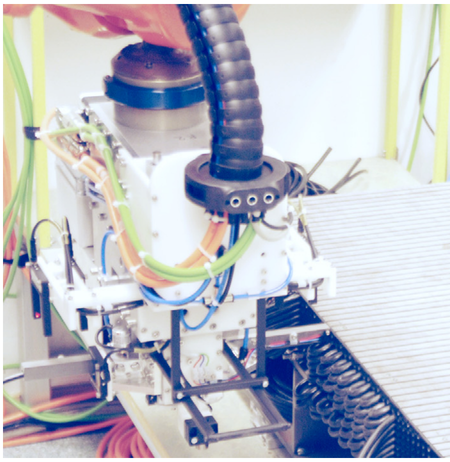


Fig. 10. Photos of the robotized stator cable winding experiments: R1 is preparing a cable end (top left), R1 is feeding the cable from the drum through the stator section and to R2 (top middle), R1 has dropped the cable and R2 is searching for the cable end (top right), the cable is fed through the stator section from R2 to R1 (bottom left), R1 is pulling the cable end while R2 is holding down the end winding (bottom middle) and R1 and R2 are pushing down the end windings (bottom right).



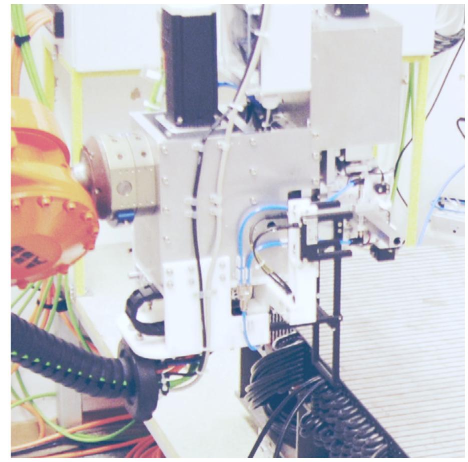


Fig. 11. (a) A close-up photo of R1 pulling the winding cable through a slot hole. (b) A close-up photo of R2 holding down an end winding being pulled by R1.

cable guiding system respectively. The miniature snap-action switches mounted at the cable guiding system ends were used to take offset measurements on the stator section side in the x-axis direction of the WOCS, as described in [5]. Hence, it was possible to compensate for irregularities in the stator section side caused by fixating the stator sheets with threaded rods in the yoke during stacking. Assuming only small local irregularities and using accumulated information from earlier measurements at nearby slot holes, the required search time was continuously minimized.

A separate sub-procedure was used for finding the cable end after pulling an end winding. This procedure included positioning the robots so that the cable could be fed backwards through the tool and out on the floor in front of the stator section. When the cable was then fed through the next slot hole, the top cable layer was always pulled first from the floor, preventing cable tangling. Searching for and adjusting the position of the cable end was performed using the cable end search function described in [5]. During this sub-procedure, the actual cable length remaining to be wound was measured simultaneously using the miniature fed distance measurement system integrated in the robot cable feeder tool [5].

Two separate sub-procedures were used for pushing and pulling the cable through the stator section. To push the cable through the stator section to the other robot was straightforward. To avoid accumulated length deviations when pulling the end winding, the actual remaining cable length—measured during the previous cable end search sub-procedure—was communicated from the other robot. We noticed that the pulled end windings were slightly too long, especially for the first end winding of each cable. This was likely due to the cable being stretched during winding. To compensate for this, the cable was pulled further according to experimentally decided values for different end winding lengths and the number of end windings previously pulled.

A separate sub-procedure was used for dropping the cable, using the procedure and supervision method described in [5] while shaking the cable feeder tool and oscillating the integrated micro push cylinders until the cable was dropped. If the drop supervision failed or if a cable drop could not be confirmed, a dialog was initiated on the HMI asking the operator to confirm the drop.

Finally, separate sub-procedures were used for holding down and pushing down the end windings. Similar positioning was used for both procedures, with the push handle close to the side of the stator section and directed downwards. To hold down an end winding, the push handle was held still just above the pulled end winding, while being pushed down against the end windings multiple times when pushing the end windings.

3.2.4. Integrated winding functions and concepts

We developed several basic help functions and integrated them into the winding control system. Four essential such functions were (1) a function used to position the robots against the correct slot holes according to the desired winding pattern, (2) a function used to automatically calculate robot positioning parameters in the WOCS relative to the current slot hole, (3) a function used to ensure equipment synchronization through handshaking and (4) a function used to supervise the robot positions in order to avoid collisions.

To further improve the winding process, we integrated several recurring programming concepts. To achieve a high accuracy in cable feeding length, we used the feeding an absolute distance function of the cable feeder tool described in [5]. Before feeding the cable, the cable gripping force was adjusted with respect to the expected feed force, reducing cable wear. When feeding cable through a half-opened cable feeder tool or moving a cable feeder tool following a cable, the feed wheels were rotated synchronously with the cable, while the cable position was supervised to improve the performance and to reduce cable wear. When feeding cable through the stator section, as far as possible, the cable was guided by the robot cable feeder tools on both sides of the stator section in order to prevent the cable from sliding against previously pulled end windings and so reduce cable wear. Finally, all robot movements were adjusted to avoid damaging the robot tool energy chain dress pack and to prevent twisting the winding cable, the latter for example by facing the robot cable feeder tools downwards during winding as described in [3,5].

3.3. Operator user interface

The complete GUI developed for the cable winding robot cell was distributed to the HMI and divided into different user permission levels. In the GUI, simple interactive buttons were combined with text, graphical illustrations and input fields. The status of the robot cell was also communicated to the operator through the signal light tower.

In the simpler operator levels, high-level process information was provided together with basic cell control and supervision functions. Minimal prior knowledge was thus required for the operator to be able to control the robot cell in these operator levels. For example, the status of the robot cell was communicated to the operator through simple and distinct emoji smiley figures in different colours, see Fig. 8a. Furthermore, high-level information about the current process running, the cell safety status, active dialogs, active warnings and active errors were always displayed. The robot cell control options included functions to

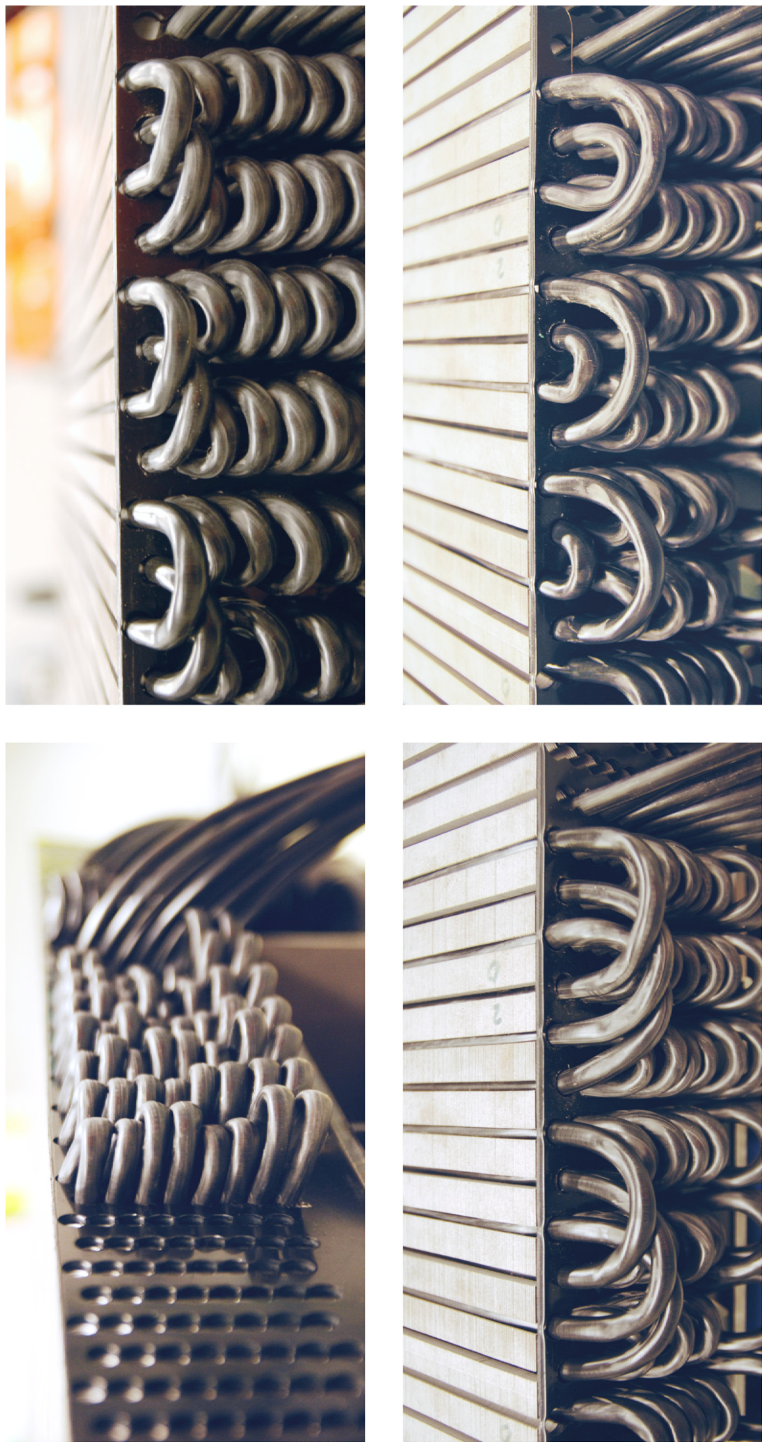


Fig. 12. Photos of robot wound stator windings: a one phase winding over 15 full slots (top left), a two phase winding over 12 slot holes in the top slot hole level (top right), a three phase winding over 12 slot holes in the top slot hole level (bottom left) and a UU WEC custom one phase winding over 12 slot holes in the top slot hole level (bottom right).

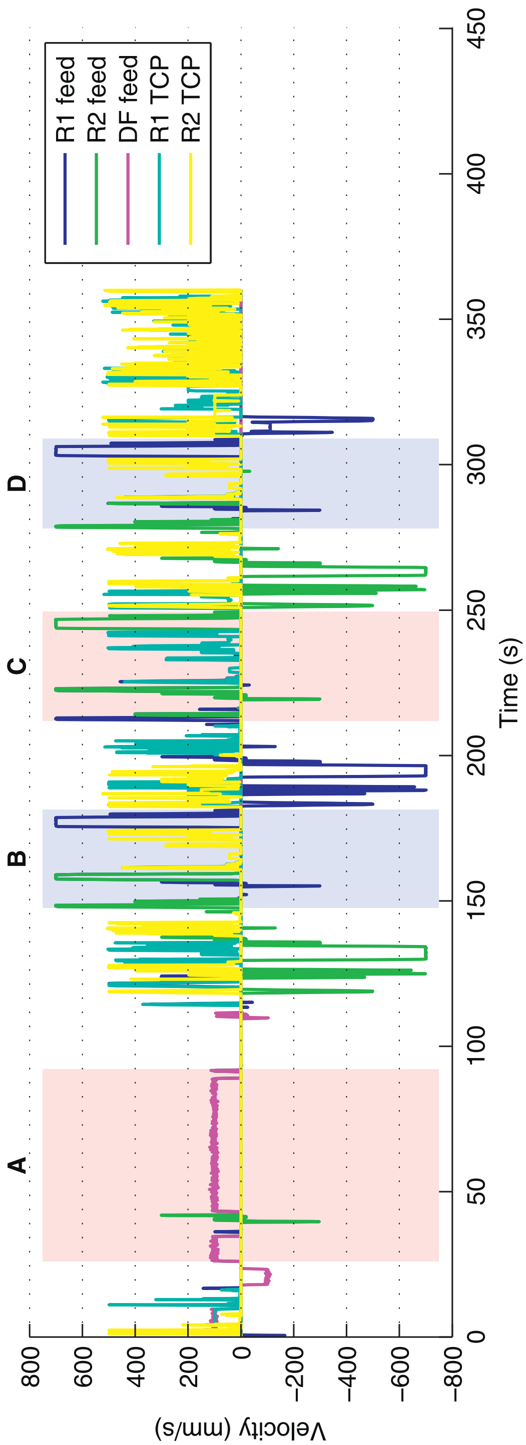


Fig. 13. The cable feed velocities for the robot cable feeder tools and the drum cable feeder tool and the industrial robots TCP absolute positioning velocities during experimental robotized winding of a cable in a three phase winding pattern over 12 slot holes. Zones A, B, C and D highlight the parts of the process when the cable is fed through a slot hole, including the robot repositioning to hold down the end winding being pulled. The parameters were logged by the PLC with sampling frequency 10 Hz.

start-up, freeze, pause, stop and shut-down the robot cell and to initiate a complete default winding process. When initiating a winding process, the winding pattern to be used was visually displayed to the operator together with estimations of the number of cables required, the length of the cables and the required process cycle time, see Fig. 9a.

The more advanced operator levels, on the other hand, provided detailed process information together with detailed cell control and supervision functions. These operator levels were thus intended to give the trained operator access to more advanced functions. For example, detailed equipment and process information were available as well as extended automatic logging of errors, warnings, process information and equipment parameters, see Fig. 8b. The advanced cell control options enabled customized winding operations, separate equipment control, service functions and GUI customization options, see Fig. 9b. Even though the expert level GUI was intended to be sufficient for most situations, complete advanced cell control and supervision did also require the use of the robot controllers teach pendants and the desktop PC.

4. Results

The final version of the developed stator cable winding robot cell was evaluated using the experimental setup and methods presented in Section 2. In the rest of this section, the experimental cable winding results are presented in Section 4.1 while analytical results are presented in Section 4.2.

4.1. Experimental results

Fully automated, robotized cable winding was demonstrated successfully in numerous full-scale winding experiments, using the third generation UU WEC stator design as an example, see Figs. 10 and 11. The HMI efficiently provided full control and supervision capabilities. All the developed control system functions, the integrated equipment functions and the GUI functions were validated. We noticed no significant equipment wear beyond what was expected.

In the experiments, simple one phase, two phase and three phase winding patterns as well as a custom one phase winding pattern used in the third generation UU WEC were performed, see Fig. 12. Fig. 13 displays selected equipment parameters during a winding process.

During the experiments, the automatic cable drop supervision function failed to validate about every tenth cable drop, as expected in [5], thus requiring the operator's attention. By estimate, one out of ten failed cable drop supervisions coincided with a failed cable drop. This could then almost every time be fixed by ordering additional robot shake movements and push cylinder oscillations. The cable drop supervision function was never observed to falsely confirm a cable drop. As expected in [4], less than one out of ten cable ends were failed in the automatic cable end insulation pull-out length inspection, thus requiring the operator's attention. Otherwise, the operator's attention was only needed to initiate the winding process and to replace the cable drum.

The remaining fatal errors occurring during the experiments were related to the characteristics of the cable or to the industrial robots. The dominating fatal error was cable kinking as an end winding was pulled, see Fig. 14. A potential beginning cable kinking error could most often be observed as a large self-contacting cable loop being formed when the cable was dropped by the robot not pulling the end winding, just before the end winding was pulled by the other robot. This loop was formed due to previous twisting of the cable, as it was fed out on and then pulled from the floor. Well-defined robot movements—when handling the cable and holding down the end windings while being pulled—did reduce this problem but could not eliminate it completely. The cable kinking was more common with longer cables and end windings being pulled between closer slot holes. By estimate, using a simple one phase winding pattern over 15 slots, fatal cable kinking errors occurred for

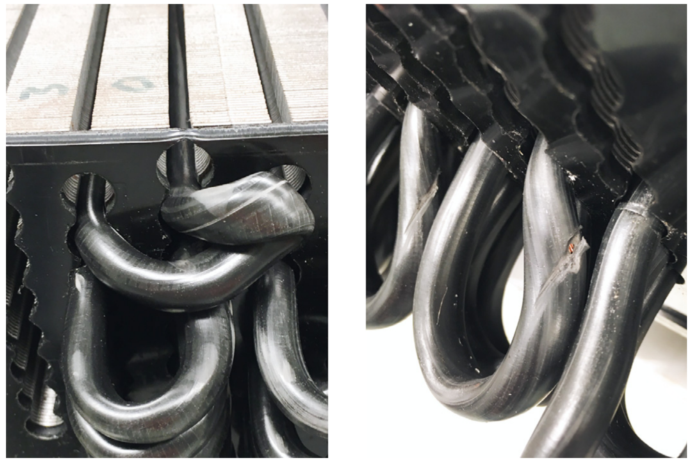


Fig. 14. Examples of failed robot-pulled end winding: a kinked end winding (left) and an end winding with a cut damage caused by the robot cable feeder tool during positioning against the next slot hole (right).

Table 2
Explanations of the different robotized winding scenarios used in the analytical robot cell evaluation. The scenarios are stated with a combination of the presented notations, where the first part represents the winding development scenario and the second part represents the third generation UU WEC stator design.

Scenario	Explanation
PR:#	The present winding method
D1:#	The moderately developed winding method
D2:#	The fully developed winding method
D3:#	The extended fully developed winding method
##:A	A nine-sided stator with nine straight sections
##:B	A six-sided stator with six straight sections
##:C	A six-sided stator with three angled sections

every 30th pulled end winding. A related error was cable tangling as it was pulled from the floor during winding. However, this only occurred once during the extensive experiments. This was when the cable was fed into a robot cable feeder tool from the floor at a higher velocity than normally used, so that it did not have time to straighten out completely while being pulled up. Another error which only occurred once was that the cable got stuck inside the stator section due to an imperfectly prepared cable end. This error could however be linked to a manual override of a failed cable end insulation pull-out length inspection. The errors related to the industrial robots all arose from using older model robots with a rather low payload capacity. Apart from a few errors related to robot wear, all these errors could be avoided by limiting the complexity and velocity of the programmed robot movements.

The quality of the performed robot windings was visually judged to be high. After calibration, the achieved end winding lengths were sufficiently precise. Little cable wear was noticed from feeding the cable through the stator. However, precautions were needed when programming the robot movements to avoid damaging previously wound end windings as a robot cable feeder tool was positioned against the stator section side, see Fig. 14.

4.2. Analytical results

By comparing experimental process cycle times with calculated cycle time estimations, the analytical winding process cycle time estimation method was validated to be accurate. Consequently, the method was assumed to provide accurate process cycle time estimations for other winding scenarios as well. In the following, we investigate the robotized winding scenarios defined in Table 2. In all the scenarios, we used an automatic conveyor belt—used to transport unwound stator sections into the robot cell from one side and wound stator section out from the cell to the opposite side—and new industrial robots. In all the further winding development scenarios, we made different assumptions on the required equipment and on the potential time savings in relation to the current PR scenario, by analysing the PR winding process in detail and using robot cell offline simulations. We assumed the UU WEC custom one phase winding pattern in all the scenarios. Fig. 15 illustrates the different winding development scenarios and Fig. 16 illustrates the stator reference designs.

In the D1 scenario, the average cable drum cable feed velocity was increased from 0.1 m/s to 0.3 m/s, the average robot cable feed velocity was increased from 0.7 m/s to 0.9 m/s and the winding process cycle time share for the robot positioning and the tooling operations—referred to as *other* below—was reduced with 30%. The winding procedure was also assumed to start from the middle of the cable and performed from the middle of the stator sections in both directions consecutively, as in manual winding.

In the D2 scenario, we used the same average cable drum velocities and robot cable feed velocities as in D1 and the other process cycle time share was reduced with 40% compared to the PR scenario. Four robots were performing winding in pairs in opposite directions starting from the middle of the stator section, as described in [1]. An additional robot was used to fetch cable from the cable drum equipment, prepare the cable ends and deliver the cable to the winding robots. It was assumed that the winding robots could work simultaneously all of the time.

In the D3 scenario, 0.3 m/s and 0.7 m/s average drum velocities and robot cable feed velocities were used and the other process cycle time share was reduced with 50% compared to the PR scenario. Four winding robots and one cable preparation robot were used. An additional robot was used together with two temporary cable storages, similar to the one described in [1], to handle the cable during the winding process. We assumed a winding procedure where the cable was pulled through two slots holes simultaneously, as described in [1]. Two additional robots were added to hold down the end windings while being pulled. It was assumed that the winding robots could work simultaneously most of the time so that the total winding process cycle time could be reduced with 40% compared to winding with two robots.

Fig. 17 shows the analytical process cycle time results for the winding of a complete UU WEC stator with the studied robotized winding scenarios. In the following, the studied scenarios are limited to PR: B and D1-3: C. The PR: B scenario is chosen because it is the most similar to the experimental setup and the stator design C is chosen because of its significantly shorter process cycle times. In Fig. 18, the analytical process cycle time results are divided into five different process operations: (1) positional calibration of the stator section WOCS, (2) cable end preparation, (3) cable feeding where the feed

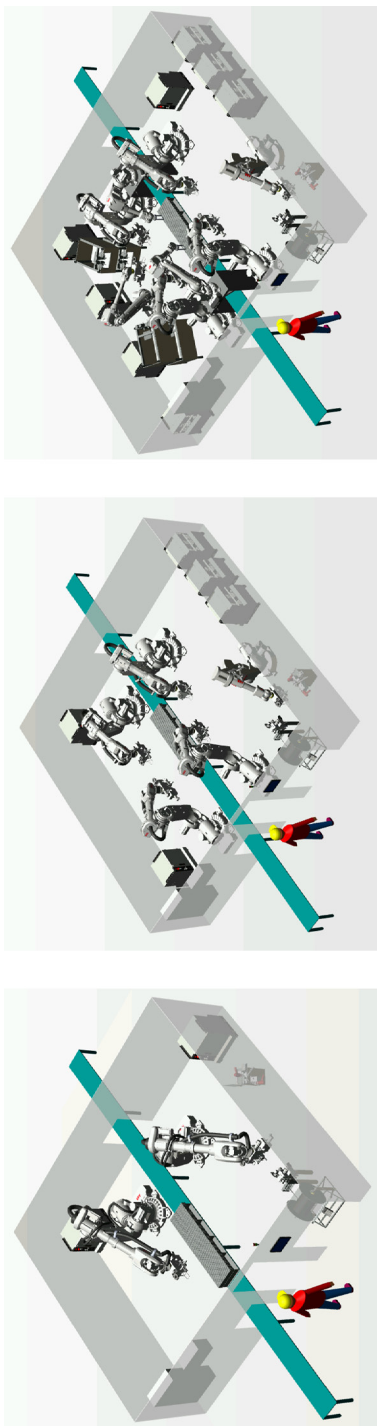


Fig. 15. Graphical illustrations of the conceptual robot cell designs, including control equipment, for winding development scenarios D1 (left), D2 (middle) and D3 (right). Note that the scaling is not the same for the illustrations.

velocity is the decisive parameter, (4) other winding activities—including robot positioning and tooling operations—and (5) standstill while waiting for the other robot pair.

Table 3 presents the parameters used in the economical comparison between manual and robotized winding. We assumed a production pace of one UU WEC generator per day. Experience has shown that stator design B is favourable for manual winding, since it is much easier to wind straight stator sections manually than angled stator sections. The manual production pace estimation was therefore taken from the manual winding experience with stator design B at Seabased Industry AB. To maximize the robot cell utilization and thus the investment capital efficiency, the robot cells were assumed to be operated over several shifts. No extra time was added to the robot winding process cycle times to compensate for winding errors, delay times or replacement of cable drums and stator sections. No extra investment cost was added to cover costs that are difficult to estimate or forecast. Fig. 19 presents the calculated accumulated costs for the studied winding scenarios. The corresponding net present values, payback periods and cost savings in relation to manual winding are presented together with the equipment utilization factor in Table 4. In Fig. 20, the total accumulated winding costs are divided into major cost unit shares.

5. Discussion

The prototype robot cell successfully demonstrated fully automated, high quality stator winding for the third generation UU WEC generator stator. The developed robot cell is flexible and well prepared for adapting the winding process to e.g. different winding patterns and stator designs. Winding with other cable dimensions is likely to be possible as well, by scaling the equipment. We have demonstrated such adaptions for the same winding concept in [3]. With a powerful standardized industrial PLC as the main process controller, a powerful but simple GUI, a distinct and simple product flow and service and commissioning functions integrated to the winding control system, the robot cell is also well prepared for future production line integration, including cloud communication. Hence, compared to the previous prototype of the stator cable winding robot cell [3], the robot cell presented here is much better prepared for industrial production integration and provides a significantly higher autonomy, flexibility, reliability, scalability, assembly quality, process forces handling capacity, user friendliness and analysis opportunities. In developing a fully automated robotized winding cable winding system, the main focus was to achieve a reliable, flexible and efficient system. Hence, as suggested in the presented winding development scenarios, further equipment and winding process performance optimizations are likely to be possible. The main challenges experienced when integrating all equipment to a complete robot cell were related to the winding procedure itself, including careful calibration of all equipment to the winding process. The long winding process cycle time and the considerable cable consumption during the experiments added further complexity to the development work. In the experiments and in analysing the robot cell performance, the special GUI in particular was much helpful.

From the analytical winding process cycle time results, it can be noted that the number of stator sections to wind is a more decisive time factor than the width of the stator sections. This is because additional robot positioning is more time consuming than winding with longer cables. While the robotized cable winding of angled stator sections has been demonstrated before [3], the winding of angled sections is likely to be possible with the updated robot cell, but this has yet to be demonstrated. A direct comparison between the presented analytical winding process cycle time estimations for robot winding scenario D3: C and the corresponding previous results [1] shows a cycle time increase of about 40% for the updated robot cell. This comparison does however also include the updated UU WEC stator design. By using the updated cycle time estimation method with the previous stator design instead, the resulting cycle time increase is about 90% for the updated

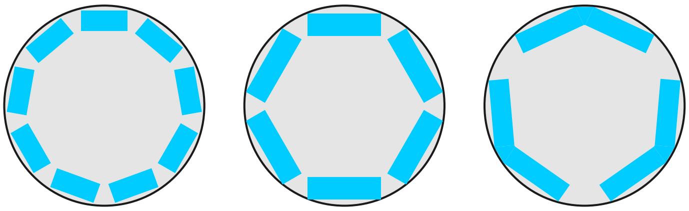


Fig. 16. Graphical illustrations of the third generation UU WEC stator designs A (left), B (middle) and C (right), as seen from the top of the generator hull. The black outer circles in the Fig. illustrates the hull while the blue rectangular parts illustrate the stator sections.

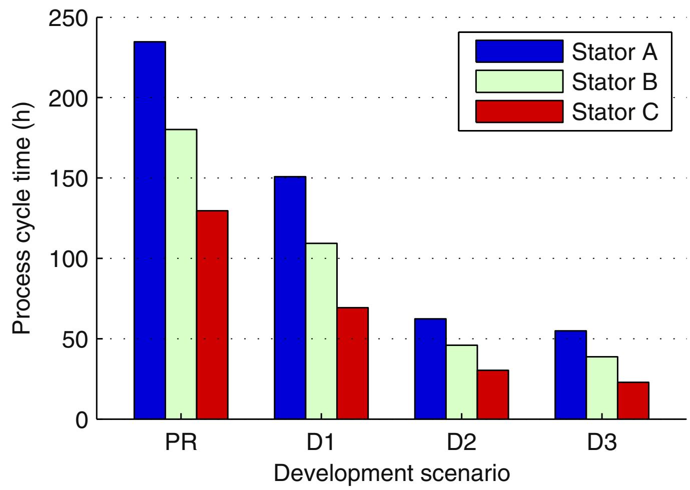


Fig. 17. Winding process cycle times per UU WEC stator for all robotized winding scenarios.

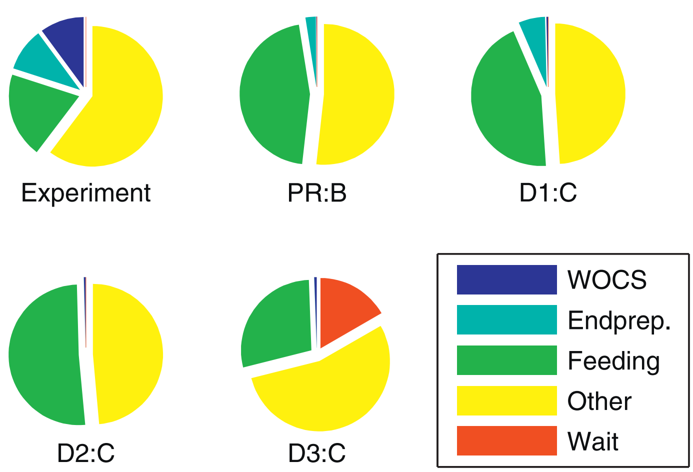


Fig. 18. Winding process cycle time shares for an experiment winding scenario and for selected robotized winding scenarios. The experiment scenario refers to the experimental setup and the winding method used in the experiments, with a one phase winding pattern over 16 slots.

robot cell compared to the previous estimation. The main reasons for this increase are that the cycle time share for robot positioning and tooling operations was significantly underestimated in the previous analytical estimations and that no wait time cycle time share was included in these estimations.

The presented economic analysis of the updated robot cell should only be taken as a rough indication of the economic potential of a fully functional robot stator winding cell for the considered application. Many parameters, such as production ramp-up time after commissioning, process wait time, future development—possibly enabling unmanned production—winding errors, and work related personnel injuries, are hard to estimate and were therefore more or less neglected in the analysis. Other parameters, such as manual winding being a very tiresome task, are impossible to include. Some height was taken for unexpected costs by assuming new robots instead of pre-owned older model robots to be used when estimating the robot cell investments costs. Nevertheless, the indicated cost savings are much lower than the previous estimations [1]. The two main reasons for this are the increase in estimated robot winding process cycle time and significant developments to the manual winding process resulting in a decrease of about 70% in the manual winding process cycle time for the third generation UU WEC stator compared to the previous scenario.

Among the potential benefits of the developed robot cell are the high and consistent quality, the very high flexibility, the extensible cell layout, the scalable production capacity and the potential cost savings compared to manual winding. Particularly appealing are the ability to automatically shift between different winding patterns and stator designs with the same equipment and the ability to handle a wide range of stator sizes and geometries with minimal need for compromises in the stator design. Automated cable winding would also eliminate a back-breaking, monotone, labour intensive and time consuming manual task, while using a simple and durable assembly method. The developed

Table 3
The calculation parameters used in the economical evaluation.

Parameter	Manual	PR:B	D1:C	D2:C	D3:C
Yearly production time (days)	225	225	225	225	225
Personnel cost (EUR/h)	20	30	30	30	30
Floor space cost (EUR/m^2/h)	0.1	0.1	0.1	0.1	0.1
Electricity cost (EUR/kWh)	–	0.1	0.1	0.1	0.1
Economical lifetime (years)	–	5	5	5	5
Discount rate (%)	–	4	4	4	4
Investment rest value (%)	–	25	25	25	25
Number of stations[a]	3	8	3	2	1
Work shifts	1	3	3	2	3
Number of personnel per station	4	0.5	0.5	0.5	0.5
Floor space per station (m^2)	35	35	35	50	55
Power consumption (kW)	–	30	30	70	100
Maintenance cost (kEUR/year)	–	15	15	35	50
Investment cost (kEUR)[b]	–	250	250	450	700

[a] The number of robot cells was estimated from the analytical process cycle time results.
[b] The robot cell's investment costs include installation and commissioning costs.

robot cell correlates well with the rising trend and demand for advanced, highly flexible, digitalized and smart automated assembly technology. Hence, the robot cell is well prepared for commercialization and could enable a broader use of cable winding technology.

Further work is however needed to further improve the reliability of the developed robot cell, before fully automated cable winding can be implemented into actual production. Since the robot cell has not been used for continuous production, further long-term experiments with different stators are needed to fully evaluate the reliability and assembly quality. The most frequent fatal winding error, cable kinking as the end windings were pulled, arose due to undesired twisting of the cable during the winding process. This problem was anticipated but more extensive than expected and was not solved satisfactorily in the presented work. Based on the here presented robotized winding experiments, fatal cable kinking errors could likely appear more than 30 times during winding a single UU WEC stator section. This is of course not acceptable in actual production, and must hence be solved either with manual assistance or with further robot cell developments. Cable twisting is common also during manual winding, but untwisting is performed almost unconsciously by the winding personnel as the ends windings are pulled. This is a craftsmanship, requiring experience as well as detailed visual and tactile feedback and interpretation, which is difficult to transfer to a robot system. Analytical methods for automatic cable shape control could indeed be implemented to the robot cell, but

Table 4
Economical parameters for the selected robotized winding scenarios in relation to the manual winding scenario, together with the utilization for the selected robotized winding scenarios in relation to the yearly production time.

Parameter	PR:B	D1:C	D2:C	D3:C
Net present value (kEUR)	−4,300	−200	300	700
Payback period (years)	–	–	4.3	2.6
Cost savings (%)	−190	−10	10	30
Utilization (%)	94	96	95 (63)[a]	95

[a] The number in parenthesis is the corresponding utilization for three shifts.

would require advanced equipment for supervision and manipulation of the cable rotation to be integrated into the robot cable feeder tools. For future work, we do therefore recommend to initially investigate simpler approaches. Examples of such approaches are to try to find a less torsional-stiff but more bend-stiff winding cable, to lay the winding cable in eights when being fed out on the floor or to use temporary cable storages during winding, and to further develop the equipment for holding down the end windings for example by forcing the end winding loop to broaden while being pulled or by pulling the end winding against something. Furthermore, while only one cable tangling error occurred during the experiments, this could become a bigger issue when winding longer cables. Hence, a temporary cable storage might be required. Winding errors related to imperfectly prepared cable ends are unlikely but could be guarded against by integrating an automatic cable end inspection, as described in [4]. Finally, the experienced winding errors related to the industrial robots would be eliminated with new industrial robots.

Several measures could be taken to increase the productivity of the robot cell while reducing the need for an operator being present, leading towards unmanned operation. Two simple measures are to improve the cable drop supervision system integrated in the robot cable feeder tools as suggested in [5] and to automatically cut off and discard cable ends failing the cable end insulation pull-out length inspection. Furthermore, the cable drum feeder tool and the cable drum feeding equipment could be updated to be able to handle drums with more cable.

6. Conclusions

We presented the first fully automated stator cable winding assembly method and validated it experimentally. The presented robot cell is adapted for the Uppsala University Wave Energy Converter generator stator, but there are many other potential applications. The

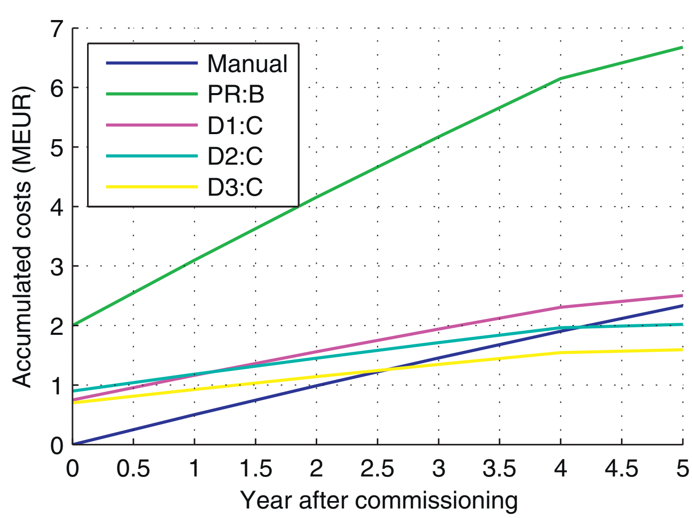


Fig. 19. Accumulated costs for the manual winding scenario and for the selected robotized winding scenarios.

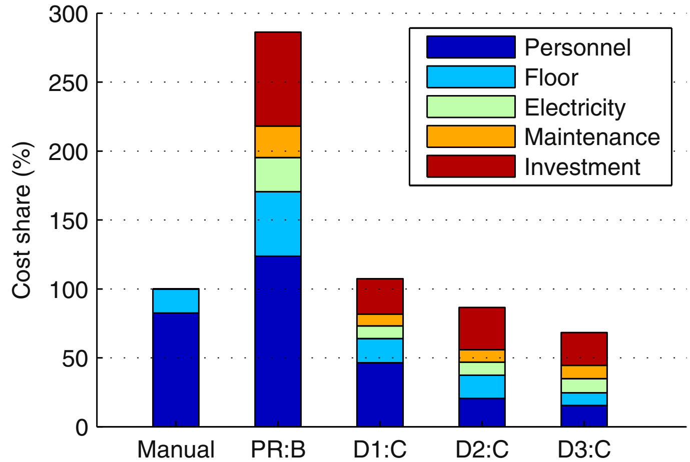


Fig. 20. Cost unit shares, relative to 100% manual cost and adjusted to present value, for the manual winding scenario and for the selected robotized winding scenarios. Note that investment rest value is subtracted from the investment cost.

benefits of our method are the high flexibility, the adaptability, the scalability, the simple and durable winding assembly and the potential cost savings as well as the elimination of a backbreaking task compared to manual winding. With its powerful process control and operator user interface, the presented advanced robot cell is well prepared for future integration in smart production lines. However, further work is needed to improve the reliability of the robot cell, mainly on preventing the kinking of the winding cable during the assembly. We have outlined suggestions on how to achieve these improvements.

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